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LONG-TERM COASTAL INLET CHANNEL AREA STABILITY

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Abstract: The equilibrium-area concept for tidal inlets has been a useful approach to understand the adjustment of an entrance channel's minimum cross-sectional area to the basic hydraulic and sedimentation characteristics of the inlet and bay it serves. This paper examines the concept in terms of inlets that apparently are not in equilibrium, maintaining a smaller area than the equilibrium area that is indicated by the Escoffier diagram. Is the Escoffier approach too simplified or is the response sometimes a very long-term process? Other methods and concepts imply equilibrium area values smaller than predicted by the Escoffier approach.

INTRODUCTION

The equilibrium area concept for tidal inlets was originated by LeConte (1905). O'Brien (1931, 1969) examined field data from tidal inlets through sandy barriers on the West coast of the United States and determined a relationship between the minimum cross-sectional flow area of the entrance channel and the tidal prism. The form of this equation is:

$$A_c = CP^n \tag{1}$$

where A_c is the minimum inlet cross-sectional area in the equilibrium condition, C is an empirically determined coefficient, P is the tidal prism (typically during the spring tide), and n is an exponent usually slightly less than unity. The empirical coefficients C and n are usually determined by the best fit to data. Recent work by Kraus (1998) derived the form of Eq. 1 by a process-based model that accounted for the dynamic balance between inlet ebb-tidal transport and longshore sand transport at the inlet entrance. Kraus obtained an explicit expression for C in Eq. 1. Hughes (2002) derived an equilibrium cross-sectional area relationship that not only matched field inlets, but also laboratory-scaled inlets, which were not reconciled by previous expressions.

Using the above equation for equilibrium area and coupling it with Escoffier's (1940, 1977) concept of simultaneously solving the analytic equilibrium area equation and the inlet's hydraulics for various channel areas of a particular inlet, one can determine stable and unstable channel areas (Fig. 1) for sandy inlets. Also, this analysis is used as a preliminary design tool to understand the inlet's response. Typically one-dimensional numerical or analytical models have been used to determine the inlet hydraulics in the initial approach. The interpretation of this curve (known as the "closure curve") has had two approaches, but Van de Kreeke (1992) clarified the interpretation that is shown in Fig. 1. Others had interpreted the area value at the peak velocity as being the location of the equilibrium area.

This concept implies that equilibrium area is achieved once the inlet's bay fills completely, i.e., the bay tide range is equal to the ocean tide range (assuming a resonant condition does not exist due to bay geometry). This conclusion is based on application of this concept to many inlets with initial bay

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14. ABSTRACT

The equilibrium-area concept for tidal inlets has been a useful approach to understand the adjustment of an entrance channel's minimum cross-sectional area to the basic hydraulic and sedimentation characteristics of the inlet and bay it serves. This paper examines the concept in terms of inlets that apparently are not in equilibrium, maintaining a smaller area than the equilibrium area that is indicated by the Escoffier diagram. Is the Escoffier approach too simplified or is the response sometimes a very long-term process? Other methods and concepts imply equilibrium area values smaller than predicted by the Escoffier approach.

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tide range values ranging from 10% of the sea tide range outside the inlet and greater. It seems intuitively correct in that, for inlets with a greater volume of water passing through in a given time period (the tidal cycle), the inlet channel will be larger. A full bay should supply greater flow power through the inlet. However, in practice, many inlets with bays that do not fill appreciably have maintained a fairly constant channel flow area over many years and do not have bays that fill completely. Important questions are, "are these inlet systems in equilibrium?" "will the entrance channel fail to enlarge?," or "will there be an eventual change over a long period?," or "could there be the possibility of a sudden scour and enlargement of the channel?" The Escoffier approach indicates the entrance channel eventually enlarges until the bay fills completely; field evidence shows inlets with apparent stable channel cross-section areas existing with bays that are not completely filling. The next section will examine some other approaches or hypotheses to determine if or how inlets can have equilibrium channels with bays that do not fill.

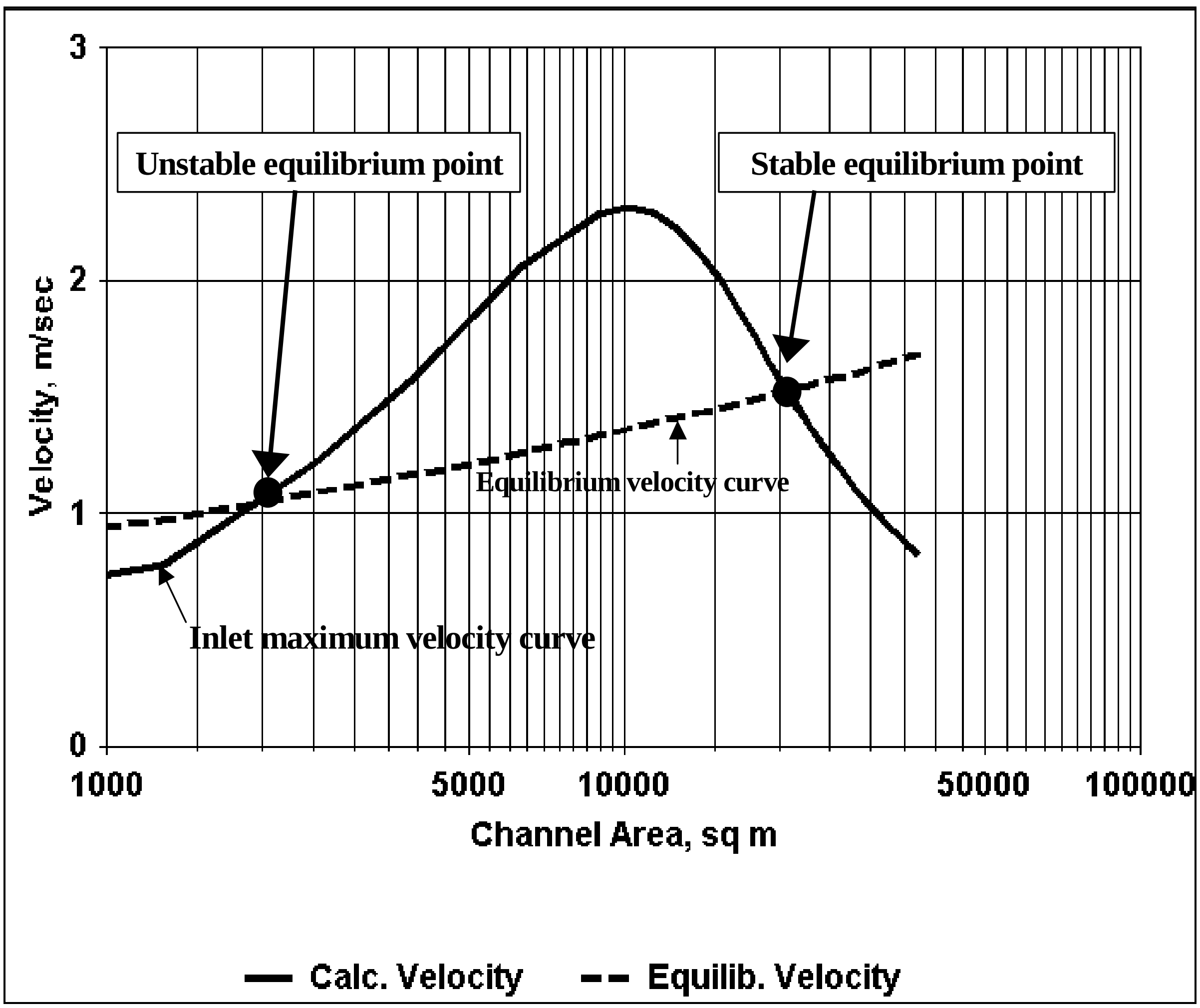

Figure 1. Escoffier's solution for an inlet's stable equilibrium area

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OTHER INLET EQUILIBRIM APPROACHES

Mota Oliveira (1970) determined from numerical experiments that for an inlet coefficient of repletion, *K*, from about 0.6 to 0.8, that the bed load capacity of the tidal currents reaches a maximum. The Keulegan (1967) "*K*" repletion coefficient, is defined as

$$K = \frac{T}{2\pi a_o} \frac{A_c}{A_b} \sqrt{\frac{2ga_o}{F}} \quad \text{with} \quad F = \sum_{i=1}^{n} k_i + \frac{fL}{4R} \tag{2}$$

where T = tidal period; a_o = tidal amplitude; A_c = the channel cross-section area; A_b = the surface area of the bay; F= the impedance of the inlet; k_i = entrance, exit and other energy loss coefficients; f = Darcy-Weisbach friction coefficient; L = channel length; and R = hydraulic radius, usually equal to the average depth of the channel. The repletion coefficient is roughly equal to the decimal fraction that the bay fills, e.g., for K = 0.6, the bay fills approximately 60 %. Therefore, Mota Oliveira's analysis supports the concept that equilibrium inlets can have bays that do not fill completely. This phenomenon of bed load capacity efficiency can be explained by the relation of water level to the time of maximum currents. For inlets that do not fill their bays completely, greater current magnitudes exist for maximum ebb flow due to their occurrence at lower water levels. Flood flow is at a higher water level, and maximum flood currents will be weaker, due to a larger channel cross-section at the higher water level. Therefore, the seaward flushing of sediments through the inlet is most efficient in the range of *K* values of about 0.6 to 0.8. This hydrodynamic process might be expected to lead to some inlets tending to be in "equilibrium" with bays that do not fill completely. It should be noted that other factors could contribute to whether tidal inlet channel currents are ebb or flood dominant. For example, Boon and Byrne (1981) showed that inlets with large open bays tend toward flood dominant currents, and inlets with bays that have highly variable areas, e.g., containing marsh and small channels, contribute to ebb dominant currents.

Skou (1990) examined the Escoffier curve and defined the response ability as "the most optimum situation for an inlet to remain stable." The response ability is determined by calculating the gradient of the Escoffier curve and plotting this slope versus the cross-section area of the inlet. The location along the curve where the gradient was a maximum defined the area that would be able to respond to change the fastest. Though Skou's interpretation did not define this as the equilibrium area, it was always larger than the "critical area," i.e., the area associated with the peak of the Escoffier curve. These two criteria will be examined for the case of a "low-*K*" inlet in the next section.

NON-EQUILIBRIUM INLETS (?)—AN EXAMPLE

Many inlets have low Keulegan *K* values. This fact indicates the inlet is not in equilibrium if the value is below 0.6 to 0.8 (by Mota Olivera's work) and below about 2.0 (the value of *K* when the bay fills completely), by Escoffier's analysis. A listing of some inlets that have or have had low *K* values is shown in Table 1. When an Escoffier analysis is performed, typically the equilibrium area is associated with the bay filling completely. An example of the Escoffier method is shown for Barnegat Inlet, New Jersey (see Fig. 2). This inlet connects the Atlantic Ocean to a very large bay (surface area of 123 million m^2) with the entrance channel passing between two parallel jetties spaced 305 m apart (see Figure 3). The inlet has sands ranging from 0.25 mm to 0.60 mm in diameter. In 1968, the bay filled only 9 % of its capacity and had a Keulegan *K* of 0.09. Fig. 2 shows the location of the 1968 area along the stability curve. Note that it was very close to unstable

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equilibrium. After significant dredging and raising the mean tide level north jetty to an above high water elevation, severe channel shoaling was reduced and the area increased to that shown for 1991 (see Fig. 2). The 1991 channel area falls on the left side of the Escoffier diagram, indicating its potential to move to the right toward equilibrium. The 1998 area reflects measurements taken after the old arrowhead jetties were streamlined to a parallel jetty system. The area has shifted further along the curve towards stable equilibrium. The equilibrium area from the graphical analysis for the existing bay is a very large 15,000 m^2 (see Figure 2). Given that the existing Keulegan *K* is less than the 0.6 to 0.8 range for *K*, and is much less than Escoffier equilibrium, it is concluded that the inlet is not in equilibrium. A short history of tidal prisms for Barnegat inlet (Fig. 4) shows that recent inlet prisms and thus inlet cross-section has been in this range of *K* for many years. There is variation that was due to improvements in the jetties and reduction in channel shoaling plus dredging. This system has a long entrance channel (see Figure 3) and perhaps the friction dominates and has helped keep the *K* value low (see Eq. 2). However, with recent improvements, a scouring mode seems to be occurring. The important question is how much scour will occur. Accepting the result of the basic Escoffier analysis, a considerable amount of scour may occur.

Table 1. Examples of "Low Keulegan *K*" Inlets In the United States*

Inlet	Keulegan *K* Value
New River, NC	0.08
Barnegat, NJ	0.09
Shinnecock, NY	0.15
Ft. Pierce, FL	0.16
Chincoteague, VA	0.16
St. Johns, FL	0.21
Indian River, DE	0.22
Ponce de Leon, FL	0.25
St. Lucie, FL	0.26
Ocean City, MD	0.29
Beach Haven, NJ	0.31
Jones, NY	0.35
Beaufort, NC	0.41
North Edisto, SC	0.42
Jupiter, FL	0.44
Winyah Bay, SC	0.45
Bakers Haulover, FL	0.45
Moriches, NY	0.54
Manasquan, NY	0.65

* Values are historical and may not accurately represent today's value.

Applying the criteria of Mota Oliveira that equilibrium would likely be in the Keulegan *K* range of 0.6 to 0.8, it can be determined from a simple one-dimensional model based on DiLorenzo (1988) and implemented in a PC based program for the Escoffier analysis (Seabergh and Kraus 1997), that the cross-sectional area for a value of *K* equal to 0.8 is 4,300 m^2. The resultant cross section would be different than the equilibrium area, found in Figure 2, of 15,000 m^2.

Determining the response ability of the channel area as discussed earlier and based on Figure 2 for Barnegat Inlet, it is seen that a channel area of about 10,000 m^2 has the highest value. This would

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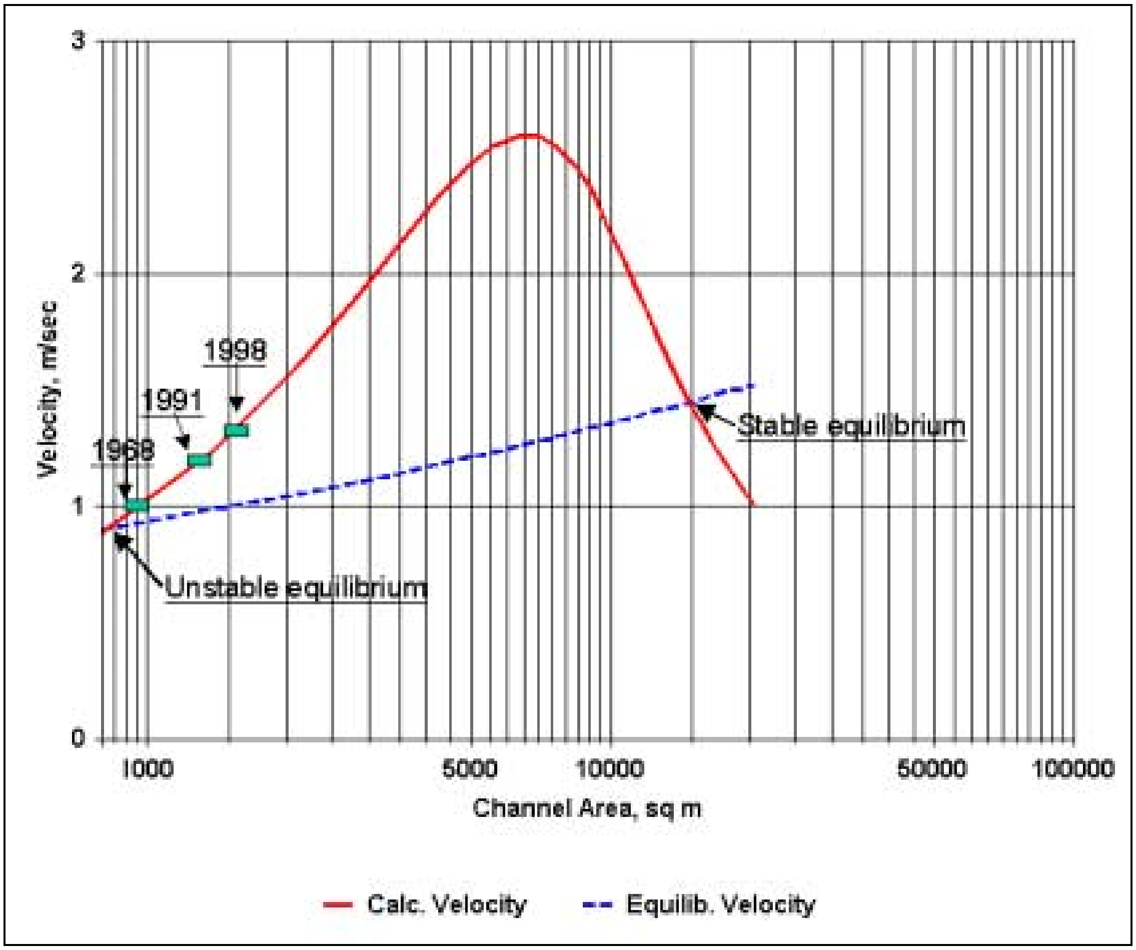

Figure 2. Escoffier diagram showing trend of movement along Escoffier curve at Barnegat Inlet, New Jersey, from 1968 to 1998

Figure 3. Barnegat Inlet, New Jersey, 1996

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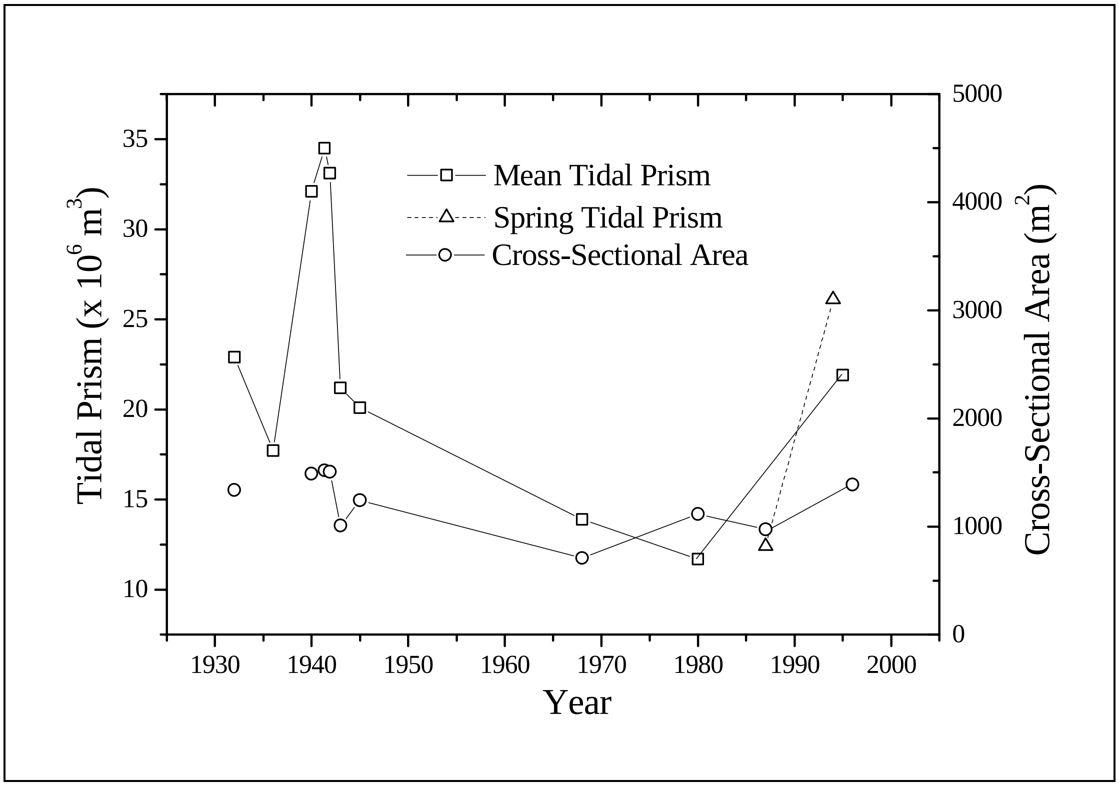

Figure 4. Changes in tidal prism and minimum cross-sectional area from 1932 to 1996

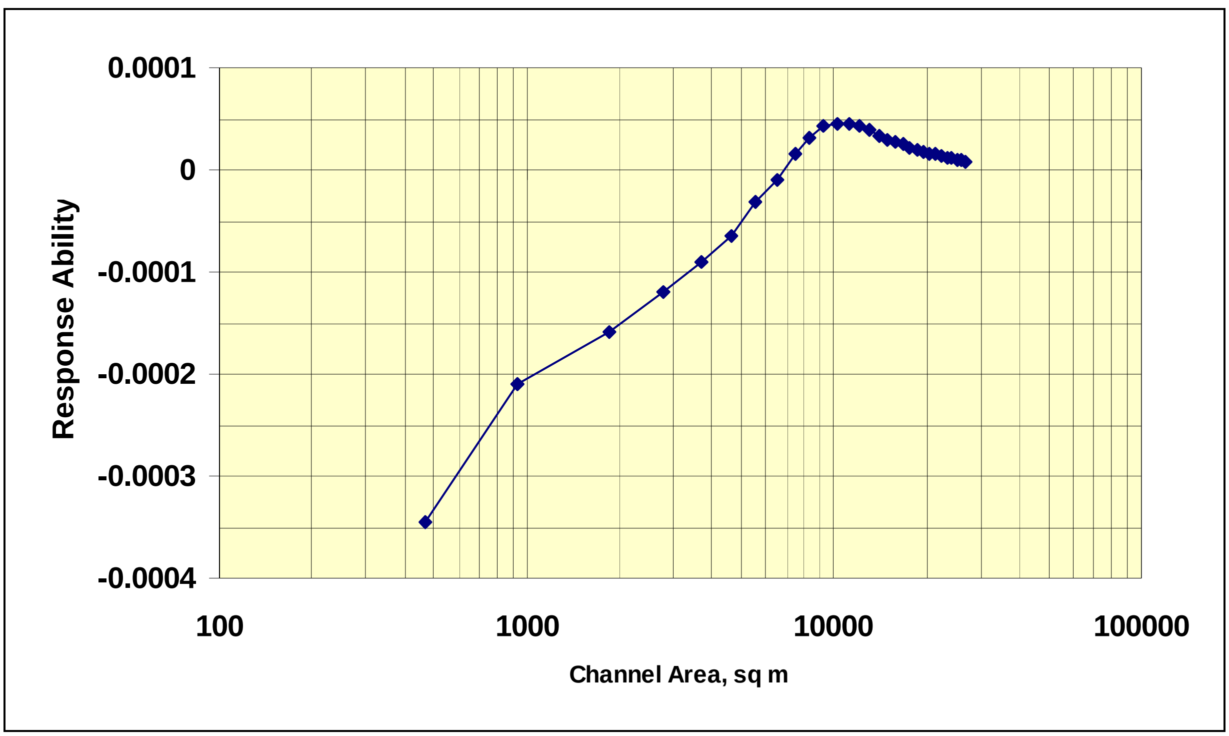

Figure 5. Response ability of Barnegat Inlet based on Figure 2

lead one to anticipate this would be the optimal cross-section area according to Skou. It is interesting to note that the response ability of the Escoffier analysis equilibrium cross-section area is about half that of the area with maximum response ability.

For the Barnegat Inlet case we have seen that anthropogenic changes between 1968 and 1998 contributed to opening the cross-section area of the inlet from about 900 m^2 to 2000 m^2. The inlet is still a low *K* inlet with a long friction dominated channel system. According to the location for equilibrium on the Escoffier analysis, the channel has a potential to reach 15,000 m^2. Using the Mota Oliviera idea that some inlets stabilize with a Keulegan *K* value in the 0.6 to 0.8 range, an expected area of 4,300 m^2 would be reached ($K = 0.8$). A value of the best channel response is achieved for an area of 10,000 m^2.

OTHER FACTORS

This relatively simple analysis indicates that it may be difficult to determine "the ultimate equilibrium area" value for an inlet. If the opportunity occurred for shortening the inlet, e.g., say an alternative shorter channel was to be dredged, or barrier beach breached, the potential for an equilibrium channel could occur. An inlet with a low Keulegan *K* value is typically a high friction loss system, so it may maintain this state for some time and may be in a "temporary equilibrium," until natural or human forces intervene. It has to be recognized that there is potential for enlargement of the channel. Nature may intervene and create a new connection to the bay due the breaching of a new inlet, creating a shorter channel from ocean to bay. With a shorter channel, friction may be less and the new cut may supplant the older inefficient channel. A larger cross-section may develop and soon a larger tidal prism could fill the bay with its attendant greater tide range, flooding areas that were dry when the old friction dominated channel-controlled flow. A storm surge could cause scour and increase channel efficiency. In a similar manner, dredged cuts to shorten navigation routes may likewise develop into more efficient channels and perhaps contribute to scour in the entrance channel as the response ability increases rapidly.

The above has discussed the negative responses of a rapid change of an inlet moving along the closure curve toward stable equilibrium. As an inlet reaches its equilibrium area, there most likely will be very positive responses occurring. Channel location stability and thus its reliability for navigation safety will be improved. The stable inlet will enhance water circulation and water quality due to a larger tidal prism relative to the low Keulegan K inlet.

CONCLUSIONS

The Escoffier analysis of tidal inlet channel cross-section area equilibrium for cases of inlets with existing low Keulegan *K* values typically indicates that the equilibrium area will be much larger than the existing area. A low Keulegan *K* inlet has a bay that only fills to a fraction of its potential tidal prism. The equilibrium channel area determined by the Escoffier analysis has a bay that fills completely. The high friction channel of a low Keulegan *K* inlet appears to be difficult to move toward the Escoffier equilibrium area unless society or nature improves the efficiency of the channel. Other approaches to an equilibrium area seem to indicate that smaller values of equilibrium other than that of Escoffier analysis may be the limiting maximum area that could exist for a given low Keulegan *K* inlet system.

A low Keulegan *K* inlet has the potential to expand its entrance channel cross-sectional area to much larger size if it is made more efficient by dredging, adding jetty structures; or if a new more efficient channel is created either by dredging, storm scour, or by natural breakthrough. The new more efficient channel will produce higher water levels in the bay due to an increase in tidal prism and potential scour until the equilibrium channel area is reached.

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REFERENCES

Boon, John D., III and Byrne, Robert J. 1981. On basin hypsometry and the morphodynamic response of coastal inlet systems, *Marine Geology*, 40, 27-48.

DiLorenzo, J.L. 1988. The overtide and filtering response of small inlet bay systems, Lecture Notes on Coastal and Estuarine Studies, Vol 29, D.G. Aubrey and L. Weishar (eds.), *Hydrodynamics and Sediment Dynamics of Tidal Inlets*, Springer-Verlag.

LeConte, L. J. 1905. Discussion of Notes on the improvement of river and harbor outlets in the United Stated, Paper No. 1009 by D. A. Watts, *Transactions, ASCE*, LV, December, 306-308.

Escoffier, F.F. 1940. The stability of tidal inlets, *Shore and Beach* 8(4), 114-115.

Escoffier, F.F. 1977. Hydraulics and stability of tidal inlets, GITI Report 13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hughes, S.A. 2002. Equilibrium cross sectional area at tidal inlets, *Journal of Coastal Research*, Vol. 18, No. 1, 160-174.

Keulegan, G.H. 1967. Tidal flow in entrances; water-level fluctuations of basins in communication with seas, *Technical Bulletin No. 14, Committee on Tidal Hydraulics*, Corps of Engineers, U.S. Army, Vicksburg, MS.

Kraus, N.C. 1998. Inlet cross-sectional area calculated by process-based model, *Proceedings 26th Coastal Engineering Conference*, ASCE, 3265-3278.

Mota Oliviera, I.B. 1970. Natural flushing ability in tidal inlets, *Proceedings 12th Coastal Engineering Conference*, ASCE, Vol III, 1827-1845.

O'Brien, M. P. 1931. Estuary tidal prisms related to entrance areas, *Civil Eng*. 1(8), 738-739.

O'Brien, M. P. 1969. Equilibrium flow areas of inlets on sandy coasts, *Journal of Waterways and Harbors Division* 95(WW1), February, 43-52.

Seabergh, W.C. and Kraus, N.C. (1997). PC program for coastal inlet stability analysis using Escoffier method, Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN IV-11, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Skou, A. 1990. On the geometry of cross-section areas in tidal inlets, *Series Paper No. 51*, Institute of Hydrodynamics and Hydraulic Engineering, Technical University of Denmark, Lyngby, Denmark.

Van de Kreeke, J. 1992. Stability of tidal inlets; Escoffier's analysis, *Shore and Beach* 60(1), 9-12.

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